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UCRL-TR-230706

Estimates of neutron reaction rates in three portable He-3 proportional counters

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Date: 2007-1-27

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Auspices Statement

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Goal

The goal of this study is to obtain Monte Carlo estimates of neutron reaction rates for the ${}^3\text{He}(n,p){}^3\text{H}$ reaction in two portable He-3 proportional counters in several configurations to quantify contributions from the environment, and optimize the tube characteristics.

Basic Model

The geometry of the model is given in figure 1. The source placed 1m above the ground is an isotropic point source made of Cf-252, and emitting $S_0=2.0\text{E}+05$ n/s into 4π . We will assume counting times of 100 and 1000 s for a total of $2.0\text{E}+7$ and $2.0\text{E}+8$ emitted neutrons respectively. The neutron energy spectrum of the Cf-252 source is modeled as a Watt fission neutron energy spectrum given in equation 1 and plotted in figure 2:

$$f(E) = \exp(-aE) \sinh \sqrt{bE} \quad (1)$$

Parameters a and b were set to 1.025 and 2.926, respectively.

The active volume of the He-3 proportional counter is a cylinder of 2.54 cm diameter by 10.16 cm long, for a volume of $5.148\text{E}+01$ cm³. We assume that there is no inactive volume. The ${}^3\text{He}$ gas is at a pressure of 6 atm and is enclosed in a 0.5mm thick steel wall. Dimensions are summarized in table1. There is no moderating material such as polyethylene around the tube. We assume the detector is carried by a person, on a belt, 1m above the ground, and 10 m away from the source.

The person is 170 cm tall and weights 68 kg. It is simulated here as a cylinder with a radius r_c of 11.2838 cm. It was previously modeled as a 170 cm high parallelepiped (see details in the simulations section). Dimensions are summarized in Table 2. We also assume it is made of water with a density of 1g/cm³. The ground is made of Portland concrete. The body and the ground scatter and thermalize neutrons and should increase the neutron flux on the detector and reaction rate in the He-3 tube

Simulations

COG simulations were run on MCR, a Livermore Computing parallel machine, where COG is a LLNL 3D Monte Carlo particle transport code. In this problem, the size of the detector is small compared to the distance to the source and the source is isotropic, hence very few neutrons are likely to reach or interact in the detector. We used source biasing to improve the variance of our estimates.

Several baseline cases were simulated:

- the Cf-252 source and the detector surrounded by air, or “free streaming” case,
- the detector is carried by a responder,
- the responder is on the ground.

As shown in figure 1, there is a direct line of sight between the source and the detector. We also simulated cases where the responder’s body is between the source and the detector. Finally, several parameters that could impact the count rate in the detector were investigated:

- Shape of the body, cylinder versus parallelepiped,
- Size, 68 kg versus 100 kg,
- Position of the detector on the responder, front versus back.
- Material composition of the ground, concrete versus soil,

- Size and pressure of the neutron counter
- Moderation with Polyethylene

Results

Numerical results are given in table 3 and 4. Columns 4 to 6 give COG estimates of the reaction rates in units of number of reactions per cm^3 per source neutron, plus the corresponding standard deviation and statistical error. These results are then scaled to the actual volume of the detector, the source intensity, and the counting time to determine the total detector count. Table 5 summarizes the percentage change in total estimated counts as a function of various parameters.

With the 68 kg cylindrical body next to the detector, the reaction rate increased by ~ 400 compared to the free streaming result, and by an additional factor ~ 2 when a thick slab of concrete was added. The weight of the responder was set to 100kg, a 4.8 cm increase in diameter, and counts increased by 13%. The changes illustrate the dominant effect of scattered neutrons on the total detector count. (see Table 3)

Preliminary MCNP simulations were done by Tzu Fong with a slightly different geometry: the responder was modeled as a parallelepiped 170 cm high * 40 cm wide * 10 cm thick. The detector was carried in the back, which meant the responder's body was between the source and the detector. There was no floor, and it is not known if the He-3 volume was surrounded by steel walls. The simulated # of counts in the detector was 4 counts over a 100s counting time. We ran a problem similar to TF and our results were in good agreement (see case rrTF in table 4). The total counts increased by 50% when changing the shape of the responder from a cylinder to the parallelepiped. By doing so, the width of the body is quasi doubled from ~ 22 cm to 40 cm, it intercepts a larger section of the beam, increasing neutron scattering towards the detector.

In all instances, the count rate decreased when the detector was placed in the back of the responder by 17% in the case of the parallelepiped and by 76 % for the cylinder. The material composition of the ground that we chose, whether concrete or soil with 5% moisture did not impact the count rate significantly compared to other parameters such as the corpulence and body shape.

We then simulated a smaller He-3 tube, 1.27 cm in diameter, and 5.08 cm in length at a pressure of 10 atmosphere. It included a 68 kg responder modeled as cylinder and the ground made of concrete. Compared to tube #1, the number of counts *per cm^3* per source neutron increased by a factor 2, however, since the volume is decreased by a factor 8, the total number of counts in the detector was lower by a factor ~ 4 . For the 68 kg parallelepiped, the detector counts increased by 50%, but remained below 3 counts over 100s. The tube was then embedded in a small polyethylene box with thin walls, ~ 1 mm thick on the top and bottom and through the diameter (rrSmtb1). For the last case, rrSmtb2, the pressure was set to 15 atmosphere. The poly box and the higher pressure did not increase the count rate significantly, the observed changes are within the statistical error of the simulations. These results seem to indicate that the smaller tube still does not meet the requirements of >3 counts over 100s of counting time.

We compared detector counts for three tubes (1.27 cm, 1.905 cm and 2.54 cm diameter) at a pressure of 10 atm. Additional variables were the 68kg parallelepiped and the ground made of concrete. Note that the length of the largest tube was kept at 10.16 cm for comparison to simulations in table 3. We determined the minimum tube length necessary to meet our requirements assuming the number of counts varies linearly with tube length. These results are

presented in table 6. The smallest tube has a 1.27 cm diameter, and the minimum length needs to be increased from 5.08 to 6.44 cm. The length of the 2.54 cm diameter tube could be significantly reduced from 10.16 to ~2.4 cm, while the length of tube with a diameter of 1.905 cm could be reduced to closer to 4 cm.

Conclusion

The smallest tube (0.5" diameter, 2" long, P = 10 atm) will not meet requirements. The largest tube (1" diameter, 4" long, P = 6 or 10 atm) will meet requirements and the tube length could be decreased to 2" at 6 atm and 1" at 10 atm. The "medium" tube (3/4" diameter, 2" long, P = 10 atm) will meet requirements for the parallelepiped body, but will not for the cylindrical body.

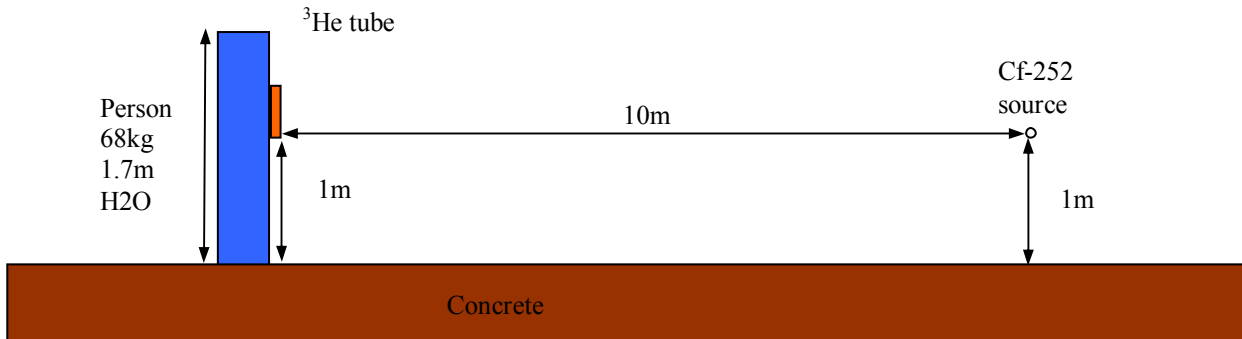


Figure 1. Simulation geometry

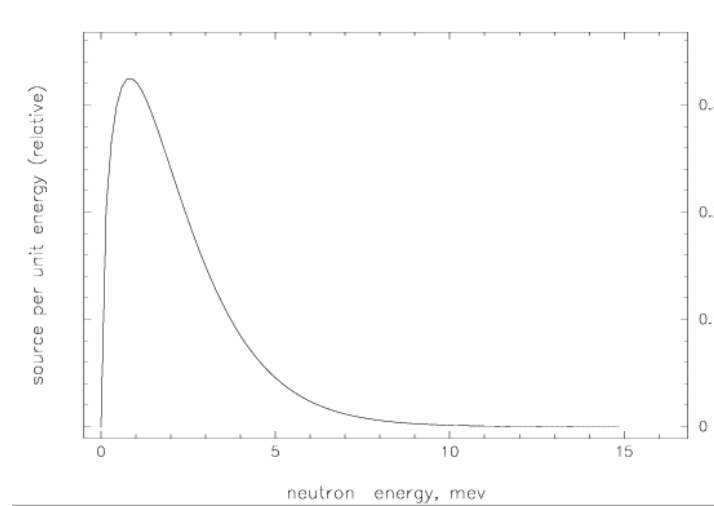


Figure 2. Watt energy spectrum. mev stands for MeV

Table 1: Tube dimensions

#	Diameter [in]	Length [in]	Diameter [cm]	Length [cm]	Pressure [atm]	Volume [cm ³]	Density [g/cm ³]	Density [atom/cm ³]
1	1	4	2.54	10.16	6	5.14815e+01	7.5228e-04	1.5021e+20
1b	-	-	-	-	10		1.2538e-03	2.5034e+20
2a	0.5	2	1.27	5.08	10	6.435185e+01	1.2538e-03	2.5034e+20
2b	-	-			15		1.8807e-03	3.7551e+20
3	¾	3	1.905	7.62	10	8.68750e+01	1.2538e-03	2.5034e+20
4*			1	3	10	9.424778e+00	1.2538e-03	2.5034e+20

* Tube #4 was not modeled

Table 2: Body dimensions (cylinder)

#	Weight [kg]	Height [cm]	Radius [cm]
1	68	170	11.2838
2	100	170	13.6836

Table 3: Results for He-3 counter type 1 (d=2.54 cm, l=10.16cm, P= 6 atm). The basic responder is 68kg, and is modeled as a 170cm high cylinder made of water. The ground is made of concrete. See the column “Description” for variations of these parameters. The count rate and total counts were obtained using a source emitting $2.e+5$ n/s in 4π .

File	He-3 tube	Description	LoS*	Reaction rate [react/cm ³ /sn]	Std dev [react/cm ³ /sn]	Rel. Error	Reaction rate [react/s.n]	Count rate [cts/s]	Total counts t=100s	Total counts t=1000s
rr00	1	Streaming	y	9.87E-12	1.38E-13	1.40%	5.08E-10	1.02E-04	0.01	0.10
rrgdc	1	Concrete only	y	1.4217E-09	1.2145E-10	8.54%	7.3191E-08	1.4638E-02	1.46	14.64
rr01	1	68kg cylinder	y	3.62E-09	7.34E-11	2.03%	1.86E-07	3.72E-02	3.72	37
rr02	1	68kg cylinder + concrete	y	6.53E-09	2.58E-10	3.95%	3.36E-07	6.73E-02	6.73	67
rrsoil	1	68kg cylinder + soil (5% H2O)	y	6.6916E-09	2.6721E-10	3.99%	3.4449E-07	6.8899E-02	6.89	68.90
rr100kg	1	100kg cylinder + concrete	y	7.4134E-09	2.7927E-10	3.77%	3.8165E-07	7.6331E-02	7.63	76.33
rr11	1	68kg cylinder	n	8.70E-10	2.03E-11	2.33%	4.48E-08	8.96E-03	0.90	9
rr12	1	68kg cylinder + concrete	n	2.2537E-09	1.63E-10	7.26%	1.16E-07	2.32E-02	2.32	23.20

*LoS: line of sight between source and detector

Table 4: Count rates in three He-3 detectors. The count rate and total counts were obtained using a source emitting $2.e+5$ n/s in 4π . The responder is 68kg, a 170cm high and made of water. See the column “Description” for variations of the body shape, tube pressure, etc...

File	He-3 Tube	Description	LoS*	Reaction rate [react/cm ³ /sn]	Std dev [react/cm ³ /sn]	Rel. Error	Reaction rate [react/s.n]	Count rate [cts/s]	Total counts t=100s	Total counts t=1000s
rrTF	1	68kg parallel. only	n	4.5927E-09	4.7669E-11	1.04%	2.3644E-07	4.7288E-02	4.73	47.29
rrTF_ft	1	68kg parallel. only	y	5.5044E-09	4.9855E-11	0.91%	2.8337E-07	5.6675E-02	5.67	56.67
rrLgtb	1b	P=10 atm + 68kg parallel. + concrete	y	1.2333E-08	4.1397E-10	3.36%	6.3492E-07	1.2698E-01	12.70	126.98
rrSmtb	2a	68kg cylinder + concrete	y	1.2392E-08	5.8897E-10	4.75%	7.9745E-08	1.5949E-02	1.59	15.95
rrSmtb0	2a	68kg parallel + concrete	y	1.8393E-08	1.2073E-09	6.56%	1.1836E-07	2.3672E-02	2.37	23.67
rrSmtb1	2a	Poly box + 68kg parallel + concrete	y	1.8535E-08	1.2289E-09	6.63%	1.1928E-07	2.3855E-02	2.39	23.86
rrSmtb2	2b	P=15 atm + Poly box + 68kg parallel + concrete	y	1.9610E-08	1.2990E-09	6.62%	1.2619E-07	2.5239E-02	2.5	25.24
rrtb3	3	68kg parallel + concrete	y	1.3419E-08	7.1156E-10	5.30%	1.9430E-07	3.8859E-02	3.89	38.86

Table 5: Summary of % changes in estimated counts, based on shape, weight, ground, pressure...



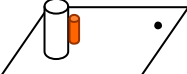
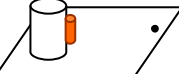


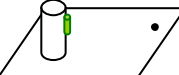
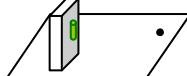
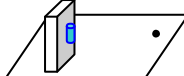
Model	Parameter of interest	New value	Change	Comments
	Basic case: detector + Cf-252 source	Large tube (#1): 1" diameter, 4" long pressure = 6 atm		
	include responder	68kg cylinder	X400	
	include ground	material = concrete	+81%	Meets requirements. (Tube #2 and #3 are compared to this case)
	nature of ground	material = soil (5%H2O)	Not significant	
	mass of responder	100kg cylinder	+13%	
	shape of responder	68 kg parallelepiped	+50%	Compared to cylindrical responder only
	position of responder	Responder between source and detector	-17%	-76% for 68kg cylinder
	type of tube	Small tube (#2): 0.5" diameter, 2" long pressure = 10 atm	-76%	
	type of tube + shape	Small tube + 68kg parallel.	-65%	Does not meet requirements
	add poly box around tube	poly box walls are 1mm thick on top, bottom and along diameter	Not significant	
	increase tube pressure	pressure = 15 atm	Not significant	
	type of tube	Medium size tube (#3) ¾" diameter, 2" long pressure= 10 atm	-42.20%	+64% compared to small tube. Meets requirements

Table 6: Minimum length of each size tube to get 3 cts in 100s. The pressure of the He-3 tubes is 10 atm, the responder is a 68k parallelepiped of water on a concrete floor,

He-3 Tube	Diameter [inch]	Tube length* [inch]	Tube minimum length [inch]
1	1	4	1
3	3/4	2	1.55
2	0.5	2	2.54

*Tube length in the COG simulation